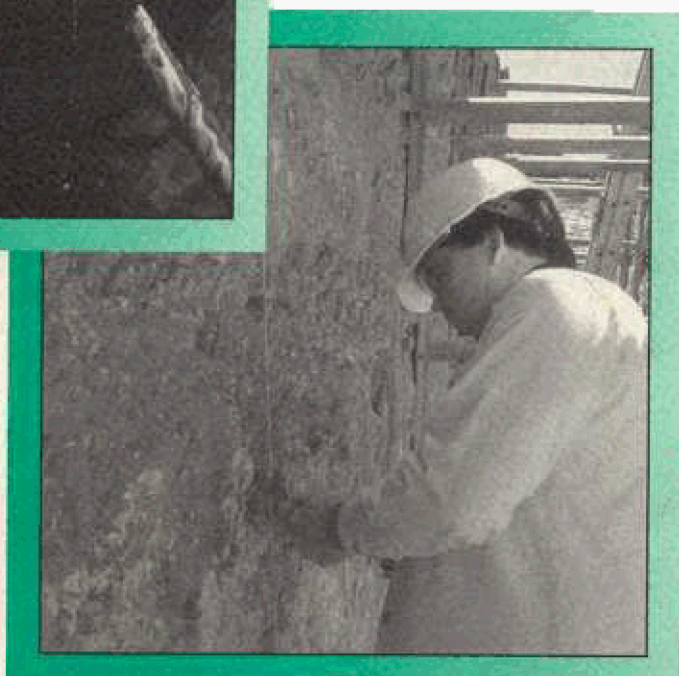
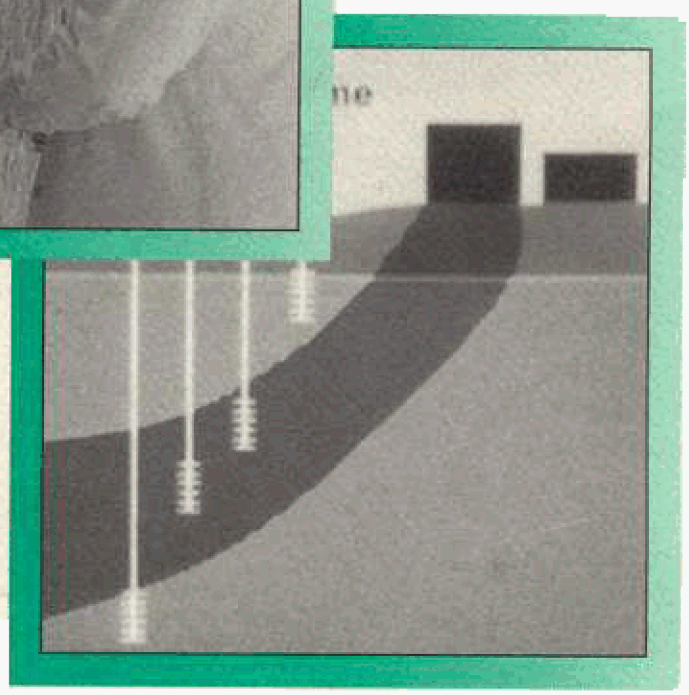
# Guidelines for Hydrogeologic Characterization of Hazardous Substance Release Sites

## Volume 2: Project Management Manual





State of California
Environmental Protection Agency

# GUIDELINES FOR HYDROGEOLOGIC CHARACTERIZATION OF HAZARDOUS SUBSTANCE RELEASE SITES

## Volume 2: Project Management Manual

July 1995

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*State Water Resources Control Board*
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*Air Resources Board*
*Department of Pesticide Regulation*
*Office of Environmental Health Hazard Assessment*

# COMMENT SHEET

This guidance document has been released as an interim final draft. The California Environmental Protection Agency will periodically revise this document to reflect the changing needs of its stakeholders and the evolving science of hydrogeologic characterization. As a user of this document, your comments are important to this ongoing process. Please use this sheet to inform us of any errors, deficiencies or suggested improvements to this document. If you identify an error or deficiency, please suggest how it can be corrected. Attach additional sheets if necessary. Send your comments to:

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Attention: Technical Guidance Work Group.

The next revision of this document is scheduled for June 1995. To allow us time to follow-up and incorporate your comments, please submit your comments by no later than January 31, 1995.

Name: Address:

Name and address are optional, but including them will help us follow-up and address your comments.

Title: Guidelines for Hydrogeologic Characterization of Hazardous Substance Release Sites
Volume 2: Project Management Manual

Section:
Comment:

Suggested Revision:

# FOREWORD

The California Environmental Protection Agency (Cal/EPA) is charged with the responsibility of protecting the state's environment. Within Cal/EPA, the Department of Toxic Substances Control (DTSC) has the responsibility of managing the State's hazardous waste program to protect public health and the environment. The State Water Resources Control Board and the nine Regional Water Quality Control Boards (RWQCBs), also part of Cal/EPA, have the responsibility for coordination and control of water quality, including the protection of the beneficial uses of the waters of the state. Therefore, the RWQCBs work closely with DTSC in protecting the environment.

To aid in characterizing and remediating hazardous substance release sites, DTSC has established a technical guidance work group to oversee the development of guidance documents and recommended procedures for use by its staff, local governmental agencies, responsible parties and their contractors. The Geologic Services Unit (GSU) within DTSC provides geologic assistance, training and guidance. This document was prepared by GSU staff in cooperation with the technical guidance work group and the RWQCBs. This document has been prepared to provide guidelines for the investigation, monitoring and remediation of hazardous substance release sites. It should be used in conjunction with the companion reference for hydrogeologic characterization activities:

*Guidelines for Hydrogeologic Characterization of Hazardous Substances Release Sites*
*Volume 1: Field Investigation Manual*

Please note that, within the document, the more commonly used terms, *hazardous waste site* and *toxic waste site*, are used synonymously with the term hazardous substance release site. However, it should be noted that any unauthorized release of a substance, hazardous or not, that degrades or threatens to degrade water quality may require corrective action to protect its beneficial use.

This document supersedes the 1990 draft of the DTSC Scientific and Technical Standards for Hazardous Waste Sites, Volume 1, Chapters 1 and 4, and is one in a series of Cal/EPA guidance documents pertaining to hazardous substance release site remediation.

## ACKNOWLEDGEMENTS

The preparation of this guidance document was achieved through the efforts of many individuals. The following people had primary responsibility for writing and editing:

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| Bill Owen | Associate Engineering Geologist, |
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Additional contributions were made by the following people:

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| Al Wanger | Associate Hazardous Materials Specialist, |
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Members of the technical guidance work group participated in the development of this document by providing comments and direction. Additional review and comments were provided by the Regional Water Quality Control Boards and Dennis Parfitt of the State Water Resources Control Board. We thank them for their cooperation and helpful suggestions.

Finally, thanks are extended to the staff of the Geological Support Unit and to the many anonymous reviewers outside DTSC, whose comments were indispensable for completing this document.

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# 1. INTRODUCTION

This volume is intended for use by project managers, consultants and responsible parties performing hydrogeologic investigations under the direction of the Department of Toxic Substances Control (DTSC). The purpose of this volume is to provide a consistent framework, applicable throughout the state, for the hydrogeologic characterization of hazardous substance release sites under the authority of the DTSC.

This volume of the Guidelines for Hydrogeologic Characterization of Hazardous Substance Release Sites describes general objectives that should be met to complete the hydrogeologic portion of any remedial investigation and feasibility study (RI/FS). It also presents a process model for the conduct of hydrogeologic investigations. A summary of the methods commonly used in hydrogeologic characterizations and general guidelines for their use are provided. Finally, minimum content and reporting requirements to substantiate achievement of these objectives are outlined. This volume discusses hydrogeologic characterization from the standpoint of project management. Implementation of the field investigation is presented in Volume 1: Field Investigation Manual (Cal EPA, 1995a).

## 1.1 Objectives

The ultimate goal of any hydrogeologic characterization is to provide information for assessing human health and environmental risks due to ground water contamination. If a risk is found, the hydrogeologic information is used to evaluate and select a remedy, and to provide data for the remedial design. Information needed from a hydrogeologic study can be provided by meeting three general objectives:

- characterize the geology and hydrogeology that affects contaminant transport,
- define the nature and extent of ground water contamination, and
- determine the hydraulic properties of the affected aquifers.

These are discussed in more detail in Section 3. Some methods and tools available to meet the objectives are discussed in Section 4.

## 1.2 Development of Methodology

An investigation methodology is developed in this document that is closely related to the RI/FS process presented by the United States Environmental Protection Agency (USEPA). The most distinctive difference is that the methodology presented here is aimed solely at ground water investigations. Project scoping, work plan preparation, field studies and the assessment of data gaps are approached from a hydrogeologic perspective. Based on this methodology, recommended approaches for reconnaissance and detailed studies are presented in Section 2.

The intended use of this document is for conducting remedial investigations and feasibility studies under the authority of the DTSC. This requires that any hazardous substance release site be evaluated for inclusion in the RI/FS process. For hydrogeologic characterization, this evaluation should assess contamination risk for ground water. Within DTSC, this evaluation occurs in a Preliminary Endangerment Assessment (PEA). The PEA is used to place sites in the RI/FS process, and is separate from the RI/FS. The substantive requirements for any PEA are summarized in Section 2. The Preliminary Endangerment Assessment Guidance Document (DTSC, 1994) should be referenced for additional information.

### 1.3 Limitations

The Guidelines for Hydrogeologic Characterization of Hazardous Substance Release Sites are part of a series of guidance documents that are being developed or revised by the DTSC. They are not intended to be stand-alone documents. Other appropriate guidance (both DTSC and U.S. Environmental Protection Agency [USEPA]) are referenced for additional information where needed.

The primary assumption implicit to these documents is that any hydrogeologic characterization is part of an RI/FS. This requires a determination that ground water contamination has occurred, or that a risk of ground water contamination exists, to initiate the RI/FS process. This initial step is made as part of the PEA. DTSC (1994) defines the role of the PEA in the RI/FS process and provides assistance in determining when hydrogeologic characterization is needed.

Investigative activities discussed in this guidance may result in disturbance to the physical environment. These disturbances, either directly or indirectly, may affect sensitive habitats or water supplies. The decision to perform any investigation warrants some level of environmental impact analysis. In most cases, formal analysis of environmental impacts is not required. However, in some instances an investigation may meet the definition of a "project" under the California Environmental Quality Act (CEQA, Section 21065, Public Resources Code), and may require a review for CEQA exemption or preparation of a CEQA Initial Study. Project managers should consult with the lead agency prior to conducting the investigation, to determine the appropriate level of environmental impact analysis.

In the broadest sense, every RI/FS follows similar processes for scoping and planning field investigations and selecting a final remedy. However, every site has a unique set of technical, logistical and budgetary constraints that affect execution of the investigation. No guidance document can account for every possible variation that may exist at every hazardous substance release site. Therefore, guidance documents are not an adequate substitute for experience. The Guidelines for Hydrogeologic Characterization of Hazardous Substance Release Sites focuses on investigative processes, methods and tools commonly used in conducting an RI/FS. Exceptions to these guidelines will occur. The selection and application of any method or tool discussed herein is the responsibility of those personnel overseeing and conducting the studies. Hence, adequate training and experience are required and independent judgement should be exercised where needed.

# 2. THE SITE CHARACTERIZATION PROCESS

## 2.1 Process Model for Hydrogeologic Investigations

The process model described in this section is illustrated in Figures 1 and 2. The model presented in this section for hydrogeologic investigations is a subset of the USEPA RI/FS process. This process is discussed in detail in Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA (USEPA, 1988).

### 2.1.1. Identification of Risk to Ground Water

An assumption implicit in the development of the process model for hydrogeologic investigations is that either ground water contamination has occurred, or a risk of ground water contamination has been identified. In California, this occurs through the preliminary endangerment assessment (PEA) process. This process is described in detail in the Preliminary Endangerment Assessment Guidance Manual (DTSC, 1994). The PEA serves as the starting point for the hydrogeologic investigation.

The hydrogeologic requirements for a PEA can be summarized as follows:

- seasonal precipitation data,
- description of hydrogeologic units,
- identification of contaminated or threatened aquifers,
- well canvassing within a three mile radius, and
- evaluate runoff potential and identify surface water receptors.

Additionally, the PEA contains provisions for ground water monitoring and sampling as needed for any given site.

Most sites in California enter the RI/FS process through the PEA. However, some sites enter the RI/FS stage without a formal PEA. This may occur by referral from another government agency, "walk-in" sites, or through public demand. Often, these sites have enough investigative data to meet or exceed PEA requirements. Where this occurs, a formal PEA is not necessary. However, for sites where available information cannot meet the substantive requirements of a PEA, a formal PEA should be conducted.

### 2.1.2. Scoping and the Conceptual Model

Scoping is the initial phase of the RI/FS process. For hydrogeologic characterization, the goals of scoping are to identify activities needed for the ground water portion of the remedial investigation, and determine the order in which these activities should proceed. Despite its conceptual nature, scoping is a very important part of the investigative process. Adequate

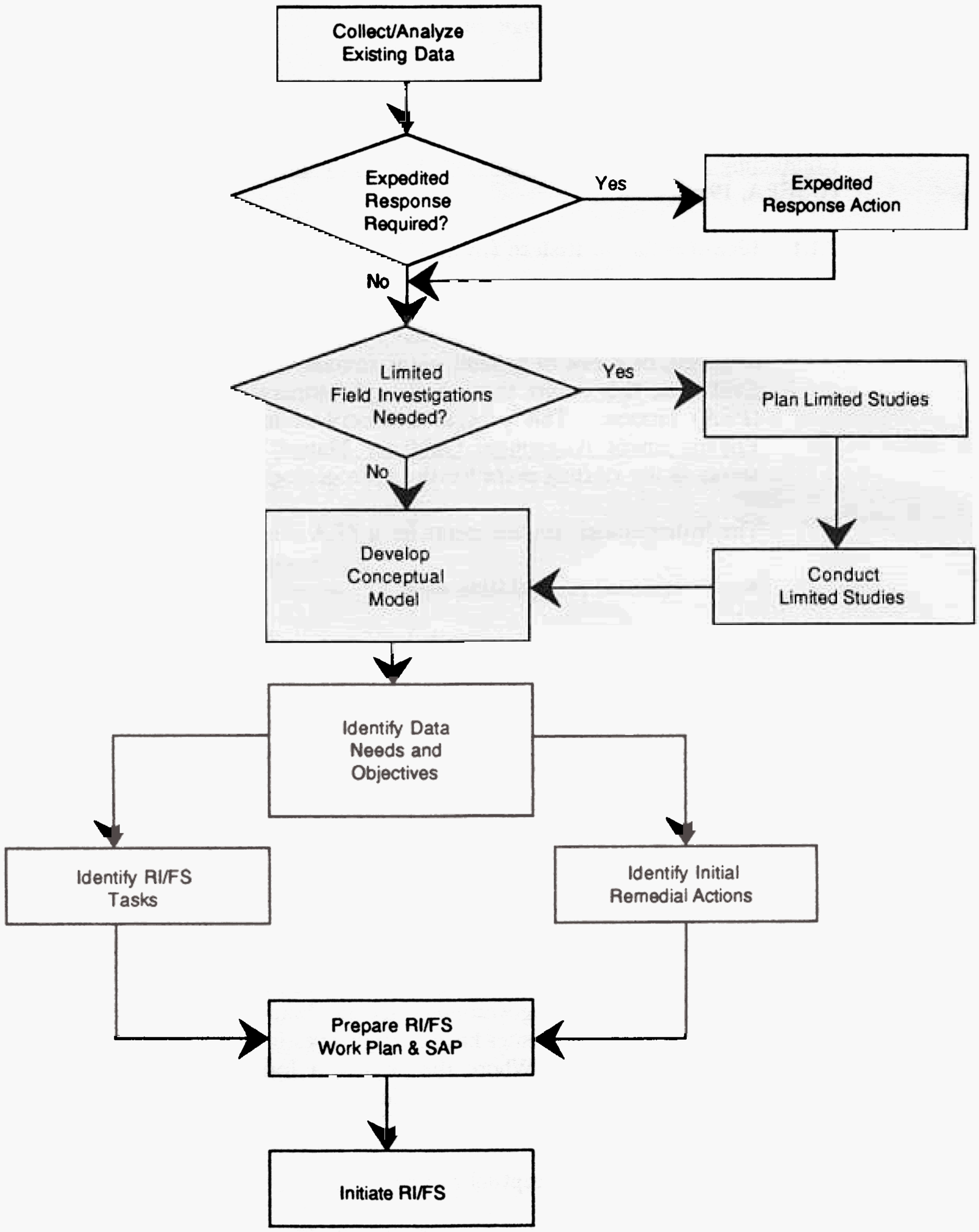


**Figure 1.** Flow chart for RI/FS scoping.

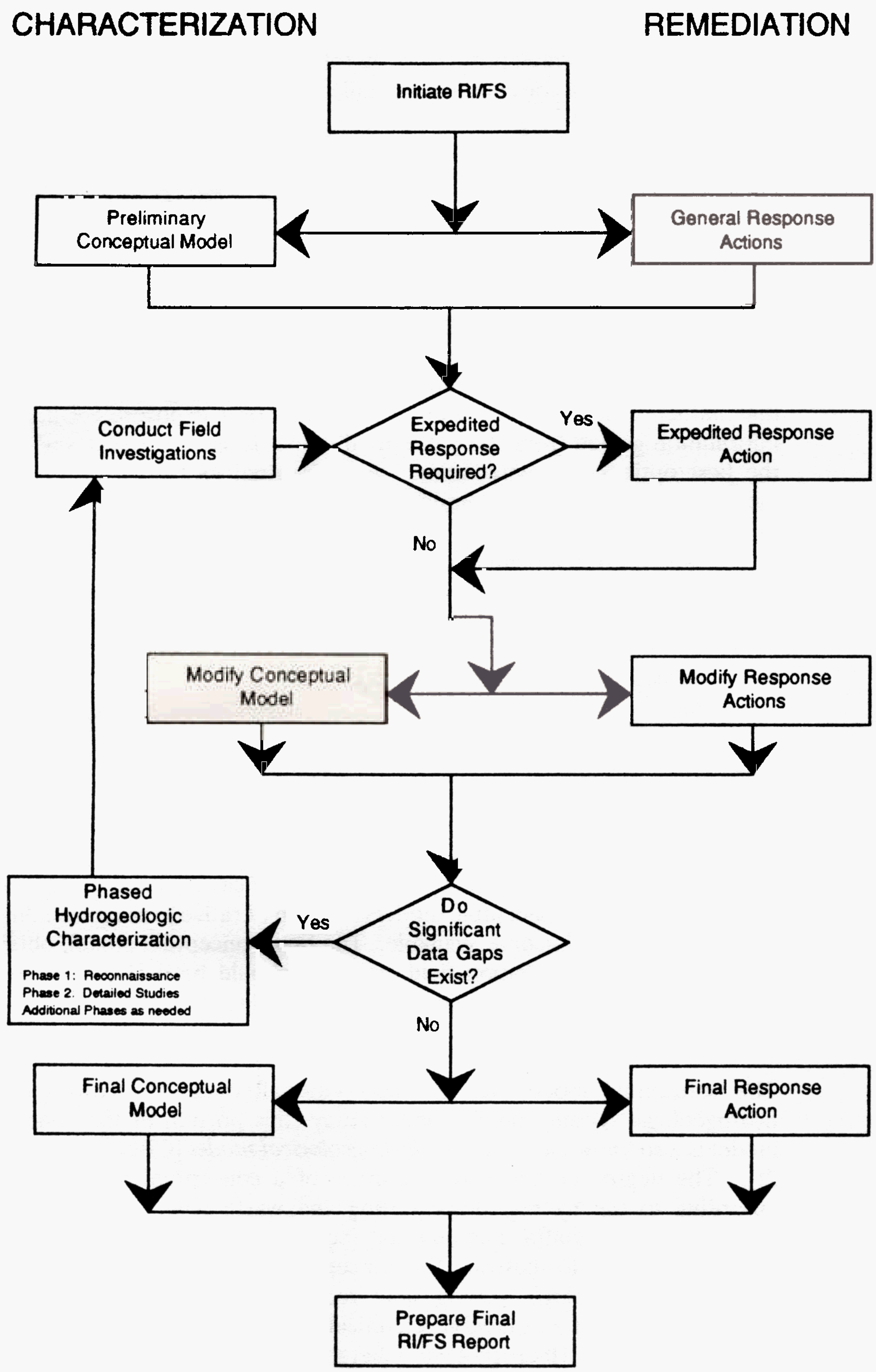


**Figure 2.** Flow chart for RI/FS hydrogeologic characterization.

scoping is crucial to assess the potential magnitude of investigative efforts and estimate the costs involved. Scoping for hydrogeologic characterization, as discussed here, is a small portion of the total RI/FS scoping. USEPA (1988) should be consulted for additional detailed discussion.

Scoping uses available information to plan investigation activities. (Some sources of information are presented in Appendix B.) As such, the quality of any project scoping is directly related to the accuracy and amount of available data. Therefore, scoping is usually an iterative process, modifying and refining the investigation as new data are evaluated.

The **conceptual model** (USEPA, 1988, p. 2-7), a narrative and graphical description of site characteristics, provides a foundation for understanding a site. The conceptual model identifies general physical conditions at a site that influence contaminant transport and receptor exposure. Ultimately, information gained from the conceptual model is used to select and design the best options for remediation. A conceptual model of a site usually includes the following key components:

- sources of contamination,
- contaminant composition,
- affected media (soil, water, air),
- routes of contaminant migration,
- contaminant receptors (humans, animals, plants).

Because project scoping relies heavily on the assessment of existing information, scoping and conceptual models are closely linked. Therefore, development of the conceptual model is also an iterative process, refining the model as new data become available. The final conceptual model, obtained through site characterization field activities, should be detailed enough to meet the characterization objectives, and provide enough information to make appropriate regulatory decisions.

The conceptual model should incorporate all essential features of the hydrogeologic system and site under study (this portion of the conceptual model is also known as a *working hydrogeological model* [CBCEC, 1993, page 2]). The degree of detail and accuracy of a conceptual model will vary according to the hydrogeologic setting and waste type. For example, a homogeneous, unconfined aquifer may require only simple cross-sections and water-table maps to illustrate the conceptual model. In contrast, a more complex hydrogeologic setting may require the above plus flow nets, potentiometric surface maps, geochemical diagrams and structure or isopach maps. Reporting Hydrogeologic Characterization Data From Hazardous Substance Release Sites (Cal EPA, 1995i) provides more information on the types of information needed to illustrate the conceptual model.

**Table 1**. Summary of ground water information needs. Adapted from USEPA (1988).

| Information Needed | Purpose | Collection Methods | |
|---|---|---|---|
| | | Primary | Secondary |
| **Geologic Aspects** | | | |
| Aquifer locations and boundaries | Define potentially affected areas | Existing literature | Lithologic sampling, water level measurements, geophysics |
| Types of aquifers (confined, unconfined) | Determine cross-contamination potential | Existing literature | Lithologic sampling, water level measurements |
| Types of porosity (granular, fractured) | Assess characterization and treatment options | Existing literature | Lithologic sampling |
| Locations of confining units | Determine cross-contamination potential, identify likely flow paths | Existing literature | Lithologic sampling, water level measurements, geophysics |
| Depth to water table | Assess potential for ground water contamination | Water level measurements | Existing literature, geophysics |
| **Hydraulic Aspects** | | | |
| Flow direction (horizontal and vertical) | Identify likely pathways for contaminant flow | Water level measurements, tracer tests | Ground water models, analytical calculations |
| Flow rates | Estimate rate of migration | Water level measurements, tracer tests | Ground water models, analytical calculations |
| Aquifer hydraulics (transmissivity, storativity) | Assess treatment options | Aquifer tests (slug tests, pumping tests) | Existing literature |
| Recharge and discharge areas | Locate potential receptors and locations for flow interception | Site inspection, field mapping | Existing literature, water level measurements |
| **Use aspects** | | | |
| Water quality | Assess exposure potential and extent of contamination | Water analysis | Existing literature |
| Water usage | Assess exposure potential | Well and surface water surveys | Existing literature |

For the hydrogeologic investigation, scoping should focus on identifying specific data needs. Existing site information should be analyzed wherever possible, to identify data gaps, initially assess the nature and extent of contamination and identify potential receptors. This analysis is the basis for developing the site conceptual model. If available data are lacking or are not adequate to develop a conceptual model, reconnaissance studies (Section 2.1.4) should be initiated to collect the needed information.

Data needs should be subdivided into two categories (that are not necessarily mutually exclusive): information for hydrogeologic characterization, and information for remedy screening (for the FS). This approach is consistent with the concept that the RI and FS are intertwined. These data needs may not be explicit during the initial scoping. Reconnaissance studies may be necessary to help define additional investigations. USEPA (1988) summarizes some potential information needs for characterizing hydrogeology, (including remedy screenings). Excerpts of these information needs are included in Table 1.

### 2.1.3. Preparation of Work Proposals

After the data needs have been identified, proposals should be made to address those needs. These proposals should specify techniques and procedures required to address the data needs, along with the supporting rationale for their selection. Under DTSC's RI/FS process, the primary work proposal is the **Work Plan**. The work plan forms the basis for carrying out field investigations, by documenting initial decisions and the evaluations made during project scoping, and defining anticipated RI/FS activities. Information typically presented in the work plan includes:

- site background and physical setting,
- summary of previous investigations,
- conceptual site model, including nature and extent of contamination and preliminary risk assessment, and
- preliminary identification of data needs and anticipated general response actions.

To the extent possible, the work plan should also specify RI/FS tasks. Work plan content, as required under DTSC remedial action orders (DTSC, 1993), is shown in Table 2.

The Field Sampling Plan (FSP) provides detailed descriptions of field sampling and investigation procedures for use during the RI. Contents of the FSP include:

- locations of sampling points,
- sampling frequency and sampling interval,

- data collection methods, and
- investigation methodology and rationale.

The FSP is written in sufficient detail such that a sampling team unfamiliar with the site could perform the field investigation using the FSP as a reference. The suggested content for an FSP is presented in Table 3.

The Quality Assurance Project Plan (QAPP) contains quality assurance and quality control (QA/QC) procedures needed to assure that quantity, accuracy and precision of the data, collected according to the FSP, are sufficient to meet the objectives of the investigation. The suggested content of the QAPP is shown in Table 4.

Because the RI/FS process is dynamic, the work plan may be modified as new data are assimilated and project goals are refined. In any case, since the QAPP is usually less site-specific, the FSP section of the work plan will generally require more modification than the QAPP for any given iteration of the RI.

**Table 2**. Recommended RI/FS Work Plan Content. After DTSC (1993). Refer to text for additional discussion of Field Sampling Plans and Quality Assurance Project Plans.

1. Project Management Plan
    - Task responsibilities
    - Organization
    - Key personnel
2. Scoping Document
    - Site background and physical setting
    - Summary of previous response actions and existing data
    - Conceptual site model
    - Scope and objectives of RI/FS activities
    - Preliminary response actions
3. Field Sampling Plan
    - See Table 3
4. Quality Assurance Project Plan
    - See Table 4
5. Health and Safety Plan
    - Description of field activities
    - Hazard description
    - Key personnel and responsibilities
    - Exposure monitoring plan
    - Protective equipment and control measures
    - Work procedures
    - Emergency response plan
    - Medical surveillance program
6. Activity and Reporting Schedule
7. Other activities as appropriate

### 2.1.4. Field Studies

After approval of the work proposals, the field studies begin. Procedures identified in the FSP and work plan are implemented to obtain needed information. Other activities (outside the scope of this guidance document) are also conducted in conjunction with the hydrogeologic field work. Additionally, discussion of project management and data management are not included in this guidance. USEPA (1988) should be consulted for additional discussion of these issues.

**Table 3**. Suggested content for Field Sampling Plans. Modified from USEPA (1988) and DTSC (1993).

1. Site Background
2. Sampling Objectives
3. Sample Location and Frequency
4. Sample Designation
5. Sampling Equipment and Procedures
6. Sample Handling and Analysis
7. Management of sample and analytical waste

**Reconnaissance Studies** are used to plan monitoring well or soil boring locations, removal actions or detailed investigations where little or no site-specific information is available. These studies are usually needed if PEA-level data do not exist, or existing data are insufficient to plan more detailed studies. Detailed quantification of hydrogeologic conditions or contaminant distribution and composition is not the primary goal of the reconnaissance study. The intent at this stage is to rapidly gather preliminary information with minimal cost and effort. Data collected from these initial studies are used to focus the efforts of subsequent detailed studies. Examples of methods and procedures typically used in reconnaissance studies include soil gas sampling, surface soil sampling, in-situ ground water sampling, geophysical studies, cone penetrometer surveys, and test pits or boreholes (most of these field methods are discussed in Section 4). Reconnaissance studies are usually undertaken during the PEA or in the early stages of the remedial investigation. However, reconnaissance studies can occur at any stage of the RI, where qualitative information is needed to focus additional investigations.

**Detailed Studies** are the comprehensive investigations constituting most of the RI field work. Accordingly, compared to reconnaissance studies, detailed studies require more planning and justification. For hydrogeologic characterization, the focus of detailed studies is on quantification of contaminant composition and extent, aquifer properties that affect contaminant migration, and the risk to potential receptors. Hence, the amount of effort expended in data collection is greater than that for reconnaissance studies. Methods and procedures used in detailed studies include, but are not limited to:

- borehole drilling,
- soil and rock coring,
- borehole geophysics,
- monitoring well and piezometer installation,
- ground water sampling and water level measurements,
- aquifer testing, and
- ground water modeling.

These methods are discussed further in Section 4.

**Table 4**. Suggested content for Quality Assurance Project Plans. Modified from USEPA (1988) and DTSC (1993).

1. Project Description
2. Project Organization and Responsibilities
3. Quality Assurance Objectives
4. Sampling Procedures
5. Sample Custody
6. Calibration Procedures
7. Analytical Procedures
8. Data Reduction, Validation and Reporting
9. Internal Quality Control
10. Performance and Systems Audits
11. Preventative Maintenance
12. Data Assessment Procedures and Corrective Actions
13. Quality Assurance Reports
14. Laboratory Certification (per California statutes)

### 2.1.5. Assessment of Data Gaps and Additional Work

As site-specific hydrogeologic data accumulates, general response actions identified during project scoping may need to be modified. Data should be evaluated to determine if the hydrogeologic characterization is adequate to screen remedial alternatives. If the data are not adequate, the deficiencies in the data base should be identified and additional work undertaken to collect the needed information. In any assessment of data gaps, the focus should be on how those deficiencies affect remedy selection. Data gaps that influence remedy selection, or are needed to adequately refine the site conceptual model, should be addressed. Data gaps that ultimately do not affect remedy selection or design, or alter the understanding of the site, may be excluded from further study. This aspect is discussed further in Section 2.3.

### 2.1.6 Removal Actions

**Removal Actions** (RA's) are short-term activities undertaken to minimize immediate risks posed by an existing or threatened release of contamination. These activities are also known as **expedited response actions** or **interim remedial measures**. USEPA (1993) classifies RA's under three categories: **emergency removals**, **time-critical removals** and **non-time-critical removals**. Often, activities involved in these removals are similar. The key differences between emergency or time-critical and non-time-critical removals are the threat to public health or environment posed by a release and the expeditiousness of the response. Under federal regulations, emergency or time-critical removals should occur within 6 months of discovery; non-time-critical removals have a lead time of 6 months or more.

Where a release or threatened release poses an imminent or substantial risk to health or environment, an emergency or time-critical removal may be employed to prevent a release of contaminants or minimize its risk. For these types of RA's, evaluation and reporting requirements are kept to a minimum to expedite the response. For non-time critical removals, however, evaluation and documentation requirements are greater. Additionally, these RA's may be subject to time and cost limits for completion. Under USEPA procedures, non-time-critical removals follow a condensed version of the RI/FS process, known as an **Engineering Evaluation/Cost Analysis** (EE/CA). Additional discussion of the EE/CA process is provided in <u>Guidance on Conducting Non-Time-Critical Removal Actions Under CERCLA</u> (USEPA, 1993). Under DTSC regulations, all RA's that do not require immediate emergency measures are conducted under an Imminent and/or Substantial Endangerment Order. Refer to DTSC (1993) for additional discussion of these requirements.

RA's can range from the simple to the complex. Examples of some activities that may be conducted as RA's are presented in Table 5. The following key concepts should be kept in mind when considering the use of an RA:

- it should reduce risk;
- it should not exacerbate the problem;
- whenever possible, simple solutions should be employed;
- wherever feasible, the RA should be designed for possible incorporation into a final remedy.

RA's can be done any time during the characterization process where a need is identified. Because RA's can quickly reduce public health and environmental risk when effectively implemented, the RA approach is recommended wherever feasible. Using this approach, it is conceivable that small sites with limited contamination and simple geology could be characterized and remediated through a series of RA's. However, the applicability of any RA should be evaluated on a site-specific basis.

## 2.2 Multi-tasking versus phased approach

A consideration in any site characterization is the management of the field investigation. One approach has been a linear, phased investigation, where each task is performed in successive iterations, each iteration having its own work proposal and data report. This approach has been streamlined over time, so that many investigations now follow a **multi-tasking** approach, where several tasks occur simultaneously or in quick succession. The differences between these two management styles is illustrated in Figure 3.

**Table 5**. Examples of Removal Actions. From DTSC (1993).

Fencing and Posting
Construction of barrier fence and warning signs to minimize direct contact

Drainage Control
Minimize direct contact and contamination of surface water

Structural Stabilization
Maintain integrity of containment structures

Chemical Stabilization
Reduce spread of release or control dangerous chemical reactions

Soil or Waste Removal, Interim Capping
Prevent direct contact and minimize spread of release

Alternative Water Supply
Provide safe drinking water to prevent consumption of contaminated water by the affected population

Interim Free-Product or Ground Water Extraction
Minimize spread of release

Multi-tasking has several benefits over the phased approach. Procedures can be developed for rapid review and approval of field data. The amount of reporting can be reduced, by writing work proposals to cover multiple phases of a project, and developing contingencies to overcome minor complications; this can result in fewer iterations of proposal preparation and review. Most importantly, the time required to complete the investigation can be reduced, enabling faster implementation of remedies. Multiple field tasks can be implemented concurrently, potentially reducing the time and cost of the investigation. For example, rapid field evaluation methods (Section 4.1) may be used for initial assessment of geology and contaminant distribution. This data can then be used to locate confirmatory soil borings and install monitoring wells in specific zones, thereby reducing the number of wells and test holes required to characterize the site. This accelerated approach can also be used for other tasks; for example, rapid dissemination of preliminary results via technical memoranda (Section 5.1), implementing contingency plans based on preliminary data, and rapid turn-around of sample analyses to avoid repeated mobilization and de-mobilization of field crews.

However, multi-tasking also has drawbacks. Management of tasks is more difficult and initial costs tend to be higher, due to the concentration of overlapping tasks around a shorter time schedule. Performing the field work requires more personnel. Additionally, the risk of error (with a corresponding increased cost for correction) is greater due to the reduced turn-around time for data analysis.

The flow charts in Figure 3 depict endpoints of a continuum. Depending on resources, budget and logistics, phased and multi-tasked management approaches can be mixed in varying degrees for any given project. Increased use of the phased approach may be appropriate for some sites, particularly where budget and resource constraints are relatively high and risk from contamination appears low. However, endless review and revision of each task (as depicted in the phased approach for Figure 3) does not enable timely implementation of a remedy and should not be pursued. The reduced time to complete an investigation, hence decreased time to implement a remedy, makes multi-tasking the preferred approach to hydrogeologic characterizations. Therefore, DTSC recommends the multi-tasking approach wherever feasible.

### 2.3 Endpoints of Investigation

In any remedial investigation a crucial question should eventually be answered: "When do we stop studying?" This is a simple question; unfortunately, it does not have a simple answer. Specific criteria can rarely be given to determine when an investigation is complete. In reality, no investigation fulfills its original objectives in their entirety. Questions always remain. Therefore, the investigation should focus on addressing significant data needs and reducing the type and number of remaining data gaps to an acceptable minimum.

Because specific objectives will vary for each site, explicit requirements for completing a hydrogeologic characterization are inappropriate. Instead, the endpoint of characterization should be based on this general criterion:

> ***Information should be known in sufficient detail to provide realistic input to the Risk Assessment and the Feasibility Study.***

For hydrogeologic characterizations, this general criterion can be subdivided into three broad objectives (discussed in more detail in the next section):

- the geology and hydrogeology beneath and surrounding the site should be understood to the extent that affected or potentially affected aquifers can be characterized and potential contaminant transport pathways defined;

- ground water contamination, or threats to ground water, should be known such that the composition, extent and amount of contamination originating from any given site can be defined, actual or potential environmental and human receptors can be determined and points of exposure can be located; and

- aquifer parameters should be measured to an accuracy sufficient for determining the rate and direction of contaminant migration, predicting the potential consequences of continuing migration and designing remedies to mitigate the affects of contamination.

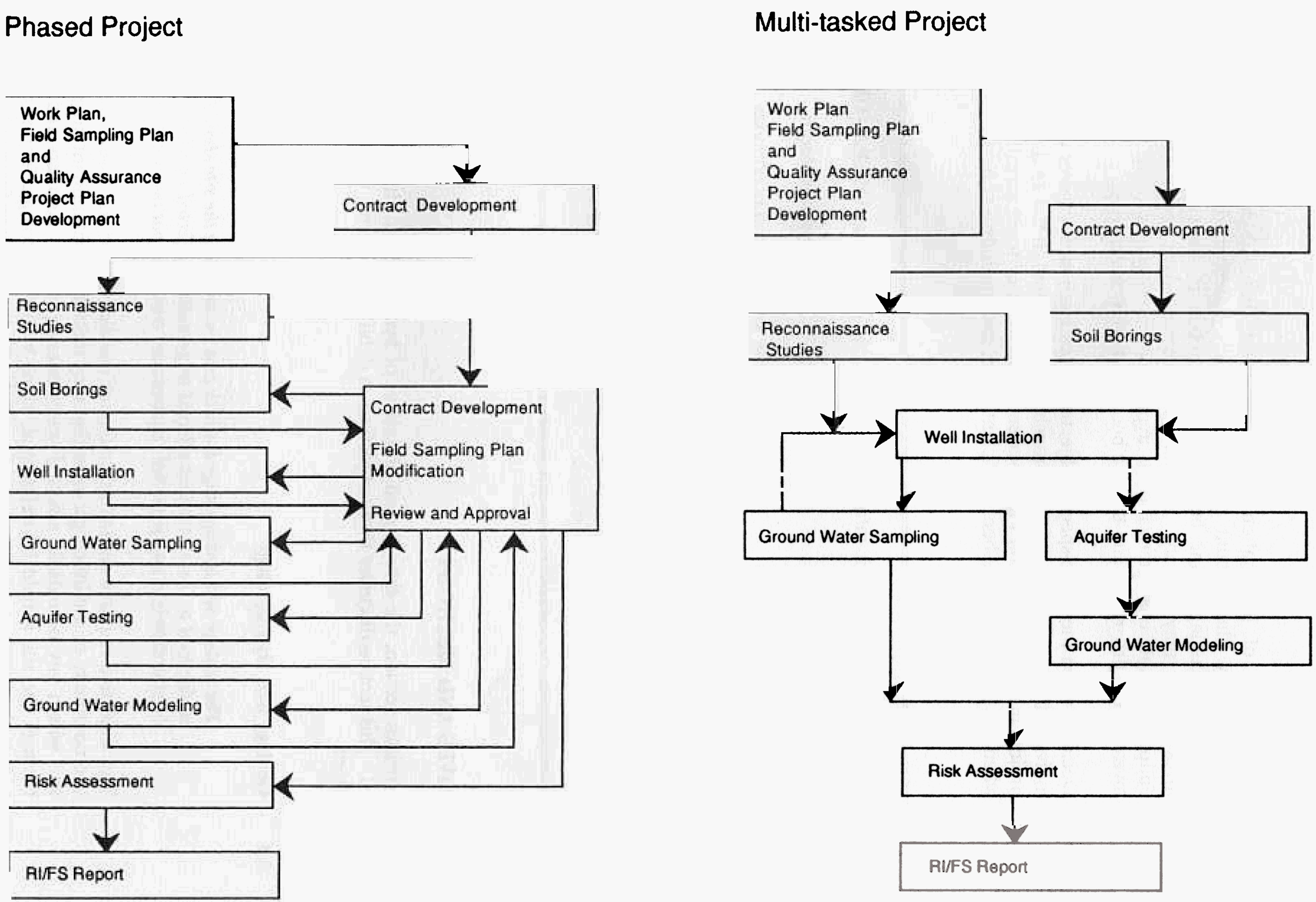


**Figure 3.** Generalized comparison of phased and multi-tasked project management. Diagrams are presented for illustration only, and are not intended to depict every aspect of site characterization.

The amount of information needed to meet these objectives is site-specific. Unfortunately, the amount cannot be initially determined with any significant certainty. Scoping at the beginning of a project is often nebulous, and initial investigations may identify additional, unexpected data gaps. Determining the endpoint of any characterization is a process that becomes more reliable as the investigation progresses and the site becomes better understood.

Deciding when these site-specific objectives have been met requires experience and individual judgement. A team approach should be used in this evaluation, with the project manager relying on the experience and input of team members in deciding when the objectives have been sufficiently met and an endpoint has been reached.

**Table 6**. Geologic and hydrogeologic information needs. Adapted from USEPA (1988).

| **Geologic** | **Hydrogeologic** |
|---|---|
| Thickness and extent of soil/rock units | Aquifer locations and boundaries |
| Lithology and mineralogy | Aquifer type (confined, unconfined) |
| Particle size and sorting | Porosity and type (granular, fractured) |
| Structure (folds, faults, unconformities) | Locations of confining units |
| Discontinuities (joints, fractures) | Depth to water table |
| Unusual features (intrusive bodies, lava tubes, solution cavities) | Seasonal water level fluctuations |
| | Recharge and discharge zones |

## 3. OBJECTIVES AND METHODS

In the previous section, the three broad objectives of hydrogeologic characterization were presented. This section discusses those objectives in detail. For clarity, the three objectives are repeated.

### 3.1 Geology and Hydrogeology

***The geology and hydrogeology beneath and surrounding the site should be understood to the extent that affected or potentially affected aquifers can be characterized and potential contaminant transport pathways defined.***

This objective requires an understanding of the distribution, thickness, composition and continuity of the lithologic units that may influence contaminant migration into and within any potentially affected water-bearing zones. Aquifers and aquitards beneath the site should be delineated, along with any geologic features that may affect ground water movement (such as faults, folds or solution features). Depths to water table should be measured, along with the composition and properties of the soil and rock in the overlying vadose zone. In addition to these factors, seasonal ground water variations, recharge and discharge zones, and beneficial uses of aquifers should be identified. This information is summarized in Table 6.

### 3.2 Nature and Extent of Contamination

***Ground water contamination, or threats to ground water, should be known such that the composition, extent and amount of contamination originating from any given site can be defined, actual or potential environmental and human receptors can be determined and points of exposure can be located.***

Data needed to fulfill this objective include sources of contamination, contaminant concentrations and composition, and the horizontal and vertical extent of contamination in both ground water and the vadose zone. Seasonal concentration changes and background concentrations of contaminants in ground water (if any) should also be assessed. These data needs are summarized in Table 7.

A common point of disagreement is whether to characterize the extent of ground water contamination to background concentrations or to a pre-set level (e.g., USEPA's maximum contaminant levels). It is the position of DTSC that the use of pre-set concentrations reduces the flexibility of the RI/FS process and, under certain conditions, leads to incomplete characterization of ground water contamination.

**Table 7**. Information needs for defining nature and extent of contamination.

| |
|---|
| General water quality (pH, salinity, dissolved solids) |
| Contaminant composition and properties (mobility, persistence, toxicity) |
| Extent of contamination (both horizontal and vertical) |
| Background concentrations |
| Seasonal concentration fluctuations |
| Sources of contamination |
| Quantity of release |

Within the RI/FS process, the baseline risk assessment is a primary tool for selecting remedial options (USEPA [1988, pages 3-20 through 3-23] provides an overview of the risk assessment process). This risk assessment provides a basis to establish cleanup levels for all contaminated media. Ground water cleanup goals may be established above background values, provided the baseline risk assessment determines that increased risk to human health or the environment would not occur, and that such cleanup goals would not would not conflict with local or regional ground water basin plans and policies. In any case, effective management of risks dictates that contamination from the site be compared to background concentrations. Failure to characterize to background may prematurely eliminate viable risk management options based solely on lack of data.

In situations where background concentrations are extremely low or non-detectable, the use of a pre-set concentration above background may fail to characterize the actual extent of contamination. A pre-set level may eliminate the collection of additional ground water data that yields important clues to contaminant transport and potential receptors (Figure 4). This may adversely influence the screening of remedies, leading to the selection of less effective remedial measures. For these reasons, all ground water contamination should be characterized to background.

## 3.3 Aquifer Parameters

***Aquifer parameters should be measured to an accuracy sufficient for determining the rate and direction of contaminant migration, predicting the potential consequences of continuing migration and designing remedies to mitigate the affects of contamination.***

This objective requires an understanding of the hydraulic properties of the aquifers under investigation. Aquifer tests should be conducted to measure transmissivity, storativity and specific yield. Water levels should be measured at different points in the aquifers to determine hydraulic gradients and velocity of ground water flow. Ground water modeling may also be necessary, to assess effects of future contaminant migration and as an aid in screening remedies for ground water cleanup. This information is summarized in Table 8.

## 3.4 Methods Available to Meet Objectives

The methods and procedures to meet the objectives for hydrogeologic investigations, listed in Sections 3.1 through 3.3, can be assigned to the following classifications:

- rapid field evaluation methods,
- surface geophysics,
- well and test hole drilling,
- soil and rock sampling,
- borehole geophysics,
- well and piezometer installation,
- ground water sampling,
- aquifer testing, and
- ground water modeling.

**Table 8**. Information needs for aquifer parameter determination.

| |
|---|
| Flow direction (horizontal and vertical) |
| Rate of flow |
| Ground water gradients (horizontal and vertical) |
| Aquifer transmissivity, storativity, specific yield |

(A)

(B)

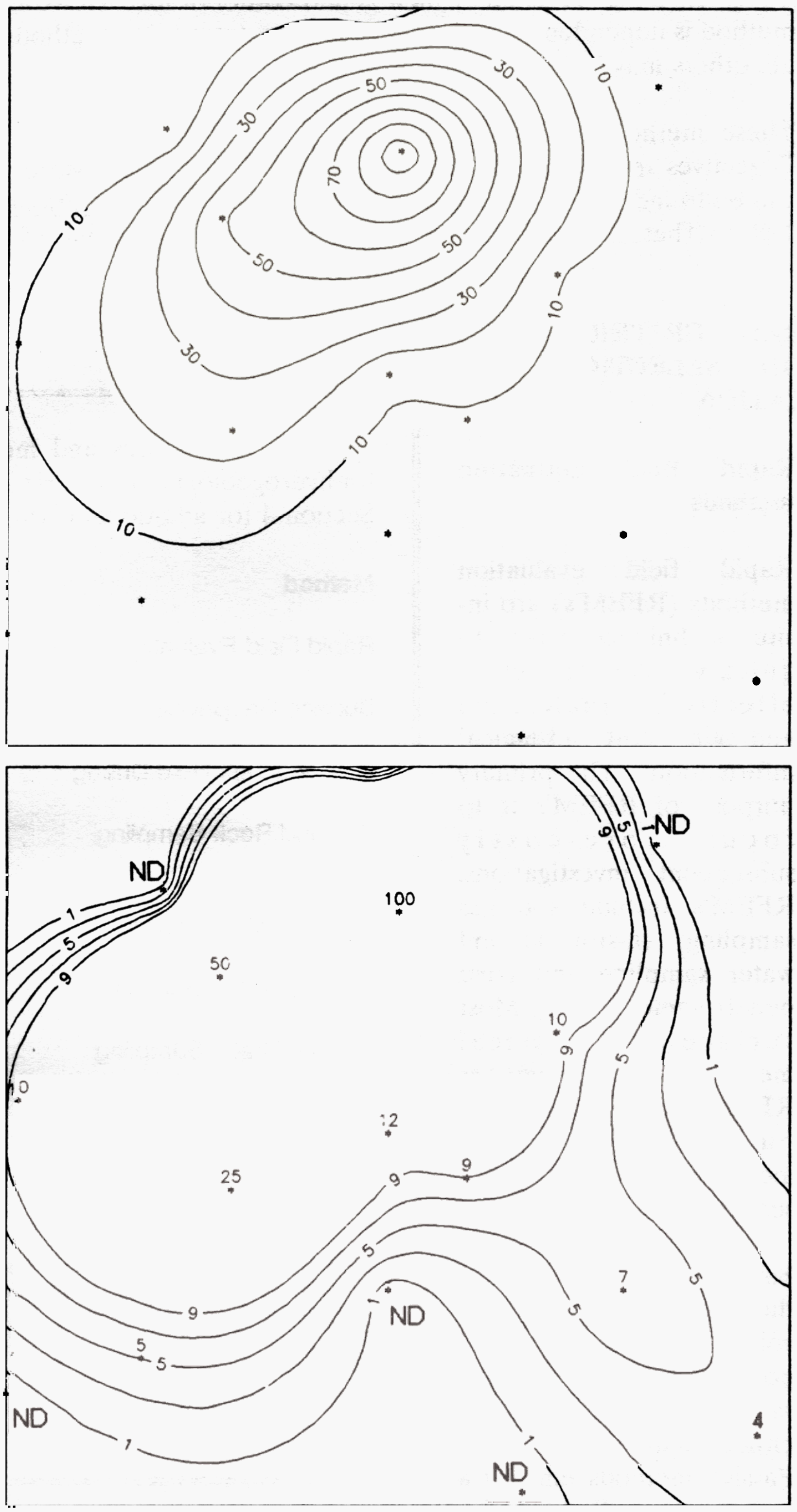


**Figure 4.** Selecting a preset remedial goal can influence perception of contamination extent. (A) Contamination defined by a 10 ug/l contour interval. (B) Contamination defined using the same data with a 1 ug/l contour interval (contours above 9 ug/l omitted). Values contoured are shown in (B).

These methods are listed by their general order of use. However, application of any method is dependent on site-specific factors (e.g., some methods may not be used at all, others may be used more than once).

These methods and procedures are briefly described in the following sections. Objectives are cross-referenced to procedures in Table 9. More detailed descriptions can be found in A Compendium of Superfund Field Operations Methods (USEPA, 1987). That document should be referenced for additional information.

## 4. GENERAL CRITERIA FOR METHOD SELECTION AND APPLICATION

### 4.1 Rapid field evaluation methods

Rapid field evaluation methods (RFEM's) are in-situ techniques used to quickly gather cost-effective, qualitative geologic and chemical information. The primary purpose of RFEM's is to focus more-costly subsequent investigations. RFEM's include soil gas sampling, in-situ ground water sampling and cone penetrometer testing. Most surface geophysical methods also qualify as RFEM's, but for discussion purposes, these are included as a separate section.

**Table 9**. Procedures and methods available for hydrogeologic characterization studies. See Section 4 for additional discussion.

| Method | Section[a] |
|---|---|
| Rapid Field Evaluation Methods | 3.1[b], 3.2 |
| Surface Geophysics | 3.1, 3.3[b] |
| Well and Test Hole Drilling | 3.1 |
| Soil and Rock Sampling | 3.1[c], 3.2, 3.3 |
| Borehole Geophysics | 3.1, 3.3[b] |
| Wells and Piezometers | 3.2, 3.3 |
| Ground Water Sampling | 3.2[c] |
| Aquifer Testing | 3.3[c] |
| Ground Water Modeling | 3.2, 3.3 |

[a]Section 3.1: Geology and Hydrogeology
Section 3.2: Nature and Extent of Contamination
Section 3.3: Aquifer Parameters

[b]Qualitative information only

[c]Primary method

**Soil gas sampling** measures the concentration or flux of volatile compounds in soil pore spaces. Soil gas sampling techniques may be either active or passive. Passive methods employ a sorbent sampling device that is buried for a specified time interval, then retrieved for sample extraction and analysis. Active methods consist of withdrawing samples of soil gas through a probe driven into the unsaturated zone. The samples are commonly analyzed by an on-site mobile laboratory. Soil gas sampling results can indicate areas of soil and ground water contamination by volatile organic compounds (VOC's), and provide a useful guide for directing further soil and ground water sampling investigations. Additionally, active methods can provide quantitative analytical data for estimating contaminant mass and risk to ground water.

**In-situ ground water sampling** operates in a manner similar to active soil gas sampling, and can often be performed sequentially with soil gas sampling during the same survey. Ground water samples are collected from a probe driven into the saturated zone. In areas where ground water is deeper than can be reached by driving, a borehole is drilled to slightly above the target depth, and the probe is driven ahead into the undisturbed formation. On-site mobile labs may be used for sample analysis. In situ ground water sampling provides one-time analytical results that can indicate areas of ground water contamination and guide the installation of monitoring wells. Appendix A (Sections A.2 and A.3) documents example applications of this RFEM.

**Cone penetrometer testing** uses probes that are pushed into the ground. The cone penetrometer probes are equipped with sensors that measure variations in tip pressure and sidewall friction as the probe advances. These measurements provide indirect information on lithologic changes (that should always be verified by direct observation) and are useful for directing detailed drilling investigations.

The most important factors influencing selection of RFEM's are the depth to ground water and the lithologic composition of the materials to be penetrated. The RFEM's discussed here all rely on pushing or driving a probe into the ground, hence these methods perform best in soils and seldom work in gravel or lithified materials. The probes can only be driven a relatively short distance, so these methods also have a practical depth limit, typically less than 100 feet (an exception is in-situ ground water sampling, which can be adapted for use in boreholes). Therefore, although still useful for shallow source characterization, RFEM's generally have limited use in areas of deep water tables or deep contamination.

## 4.2 Surface geophysics

Surface geophysics is the term used to describe a broad class of remote sensing techniques. These techniques utilize indirect measurements of material properties, to define geologic and hydrogeologic features that cannot be directly observed. Surface geophysics are distinguished from borehole geophysics in that for the former, measurements are made at or near the ground surface, whereas the latter are made within a borehole. Surface geophysical techniques are classified by the physical property being measured. The primary methods are:

- **resistivity**, used in geologic and hydrogeologic interpretation, involves the measurement of electrical resistivity made by passing electrical currents directly into the earth;

- **electromagnetic**, similar to resistivity, but measurements are made via induced electromagnetic fields rather than direct measurement of electrical currents;

- **seismic**, including reflection and refraction, is used for geologic and hydrogeologic interpretation and measures the passage of acoustic waves through the earth;

- **radar**, also known as ***ground penetrating radar***, is similar to seismic reflection, but utilizes electromagnetic rather than acoustic energy; primarily used to locate waste containers, disposal areas and underground utilities;

- **magnetometry**, with uses similar to radar, measures changes in the ambient magnetic field caused by the presence or absence of magnetic materials;

- **gravimetry**, the measurement of minute changes in the Earth's gravitational field caused by differences in the distribution of mass; used mainly for regional geologic studies.

The results of surface geophysical surveys are interpretive and should be confirmed by direct observation. Although not definitive, these surveys are a cost-effective means of gathering substantial amounts of information to focus subsequent studies. Application of Surface Geophysics at Hazardous Substance Release Sites (Cal EPA, 1995b) provides additional QA/QC recommendations for surface geophysical surveys.

### 4.2.1. Qualitative and quantitative interpretation

In any discussion of geophysical techniques, a distinction should be made between quantitative and qualitative interpretation of geophysical data. ***Quantitative*** interpretation involves the derivation of numerical values for specific physical properties, based on the measurements. Rock density, seismic velocity and depth to ground water are examples of quantitative interpretations. ***Qualitative*** interpretation, on the other hand, is the estimation or identification of materials and material properties based on data variations within a particular study area. Drum locating, waste pile locating and underground utility detection are examples of qualitative geophysical interpretation.

Geophysical methods may be used qualitatively or quantitatively, depending on the data needs. Data collection for quantitative interpretation is more expensive and involved, but the resulting interpretation is usually of better quality and more defensible than qualitative interpretations. Data collection for qualitative interpretation is faster and less expensive, but uses of the data are limited. Qualitative surveys are useful for reconnaissance studies and removal actions, where only coarse information is needed. Quantitative surveys are good for detailed studies, where more specific information may be used to reduce the number of boreholes and monitoring wells needed at a site. These uses are by no means absolute: a combination of qualitative and quantitative surveys is possible. Project budget and data needs will dictate how and when these surveys are conducted at a site.

### 4.2.2. Factors influencing method selection

Table 10 shows applications and limitations of commonly used geophysical methods. In general, all quantitative survey methods work best in areas of minimal human development. Buildings, vibrations and stray electromagnetic fields can limit the effectiveness of quantitative surveys. Complex geologic conditions can also limit interpretation accuracy. Qualitative interpretations may be the only ones obtainable in areas of heavy development or complex geology. In any case, a knowledge of site-specific field conditions is a prerequisite for planning any geophysical survey.

## 4.3 Well and test hole drilling

When ground water monitoring and soil sampling locations have been determined, drilling is used to reach the designated monitoring and sampling depths. Drilling methods commonly used in hydrogeologic investigations can be divided into three types: hollow-stem auger, mud rotary and air rotary methods.

**Hollow-stem auger** drilling uses a hollow drilling stem attached to a continuous auger blade. Drill cuttings are removed by auger rotation. Undisturbed soil samples are collected by driving a sampling device ahead of the drill bit through the hollow stem. Monitoring wells are likewise constructed through the hollow stem. Drilling fluids are not used with this method.

**Mud rotary** methods use water mixed with viscosity-increasing additives to aid in drilling. Drill cuttings are removed by circulation of the drilling fluid. Cuttings may be lifted to the surface outside the drill stem (direct mud rotary), or raised through the stem (reverse mud rotary). Soil sampling occurs by removing the drill bit and advancing a drive sampler through the bottom of the hole, or sampling may be performed through the drill stem with the bit in place by using specially designed samplers and drill bits. Monitoring well construction should be performed with the drill bit and stem removed from the hole.

**Air rotary** methods are similar to mud rotary, but use air or air mixed with foaming agents as the drilling fluid. Air rotary rigs may be either direct or reverse circulation, but the most common air rig used for hazardous waste work employs reverse circulation. Often, casing is advanced during drilling to stabilize the hole. Some air rotary rigs are also convertible to mud rotary drilling. Soil sampling and well construction are similar to mud rotary methods.

Other drilling methods include cable tool, dual-tube percussion and dual-wall reverse circulation (a modification of mud rotary). Other methods are also available, but are used infrequently or are not suitable for environmental work. Drilling, Coring, Sampling and Logging at Hazardous Substance Release Sites (Cal EPA, 1995c) provides additional information on these and other drilling methods.

**Table 10**. Applications and limitations of commonly used surface geophysical techniques.

| Method | Use | Maximum Depth[a] | Advantages | Disadvantages |
|---|---|---|---|---|
| **Resistivity** | Geologic features[b] Hydrogeologic features[c]. Tank, pit and landfill locating Locate buried utilities[d] Locate contaminant plumes[d] | >100 | Good vertical resolution (lateral resolution dependent on survey mode)<br><br>1-D or 2-D interpretation possible, depending on survey mode | More time-consuming than EM<br>Decontamination of some equipment components may be needed<br>Susceptible to stray EM fields and buried metal pipelines |
| **Electro-magnetics (EM)** | See Resistivity | 50 | Inexpensive. Rapid measurement<br>Good lateral resolution<br>1-D or 2-D interpretation possible, depending on survey mode | Poor vertical resolution<br>Limited dynamic range<br>Susceptible to stray EM fields and nearby metal objects |
| **Seismic** | Geologic features Hydrogeologic features Excavation potential Foundation studies | >100 | Good for large area reconnaissance<br>Good vertical and lateral resolution<br>Good definition of geologic/ hydrogeologic structures | Susceptible to vibration noise<br>Field operations more complex than for other geophysical methods<br>Decontamination of some equipment components may be needed |
| **Radar** | Tank, pit and landfill locating. Geologic features[d] Hydrogeologic features[d]. Locate contaminant plumes[d] | 30 | Rapid measurement. Real-time results<br>Excellent lateral resolution<br>Excellent penetration in dry, sandy soil | Radar penetration extremely limited by clays, saline soil, groundwater<br>Some equipment susceptible to stray EM fields |
| **Magnetics** | Tank, pit and landfill locating<br>Geologic features[d] | >100 | Inexpensive<br>Rapid measurement<br>Good lateral resolution | Susceptible to stray EM fields and nearby ferromagnetic objects<br>Quantitative interpretation difficult |
| **Gravity** | Geologic features<br>Tank, pit and landfill locating[d] | >100 | Good for large area reconnaissance<br>Good for landfill siting and evaluation of regional geology | Rarely feasible for detailed studies Extensive data reduction and correction needed for interpretation |

[a]Depth to target in feet. Values are approximate.
[b]Geologic features include stratigraphy and geologic structure.
[c]Hydrogeologic features include depth to water table, aquifers and aquitards.
[d]Secondary use (applicable under limited circumstances).

### 4.3.1. Selection of method

Criteria for the selection of drilling methods are presented in Table 11. In general, depth to target, cross-contamination potential, and the need for chemical sampling and well construction all influence the selection of a drilling method. When sampling soils for chemical analysis, hollow-stem auger is the preferred method. However, maximum drilling depth for most hollow-stem auger rigs is roughly 125 feet. Hollow-stem auger rigs with deeper capability are available, but currently only on a limited basis. If deeper targets are sought, rotary or percussion methods may be needed. Hollow-stem auger drilling can smear clay on the borehole wall, reducing permeability across it. This effect is most pronounced in interbedded sand and clay, and usually cannot be overcome by normal well development procedures. The effects of smearing can be minimized through appropriate drilling procedures (e.g., reaming) but, in general, hollow-stem auger is not recommended for installing monitoring wells in thinly bedded clay- or silt-bearing formations. The potential for cross-contaminating aquifers requires sealing off individual aquifers while drilling. This requires the installation of telescoped conductor casing or the use of methods that drive casing while drilling. Cal EPA (1995c) provides additional discussion of drilling methods and procedures.

### 4.3.2. Compatibility with geophysical logs

Any borehole that is not continuously sampled should be logged using borehole geophysical methods, unless shallow depth or instability makes the hole unsuitable. Since geophysical logs work best in open holes, open-hole drilling methods should be used whenever possible. The exception is where cross-contamination risk or hole instability dictates the use of casing while drilling. (This also severely limits the types of geophysical logs that can be used.) Although some geophysical logs can be run in dry holes, fluid-filled holes allow for a wider selection of geophysical logging tools. Therefore, mud rotary methods are the first choice for geophysical logging. For monitoring well installations, if mud invasion into an aquifer is a concern, a pilot hole can be drilled using mud rotary. After logging, the hole can be subsequently reamed to the target depth using air rotary. Application of Borehole Geophysics at Hazardous Substance Release Sites (Cal EPA, 1995d) provides more discussion of tool selection and drilling methods for geophysical logging.

## 4.4 Soil and rock sampling

Soil and rock sampling may be divided into two categories: disturbed and undisturbed. **Disturbed samples** consist of disaggregated material that is not representative of its initial condition. Examples of disturbed samples are drill cuttings and surface scrapings. **Undisturbed samples** are more representative of their initial condition. "Undisturbed" is a misnomer, since every sample is disturbed to some degree during collection. Undisturbed samples, in reality, are samples that have been collected in a manner that minimizes disturbance, such that they can be considered reasonably representative of the material from which the sample was collected. Examples of undisturbed samples include rock cores, and soil cores collected from thin-walled samplers.

**Table 11**. Drilling methods for various geologic settings. After USEPA (1991).

| Geologic Setting | Drilling Methods | | | | |
|---|---|---|---|---|---|
| | Air Rotary[1,2] | Mud Rotary[1] | Hollow-Stem Auger[3] | Percussion[4] | Dual-Wall Reverse Circulation |
| Unconsolidated, poorly consolidated materials less than 125 feet deep | good (casing required) | good (mud invasion in vadose zone possible) | good (cobbles may limit penetration) | good (cable tool inefficient) | excellent |
| Unconsolidated, poorly consolidated materials more than 125 feet deep | good (casing required) | excellent | marginal (limited availability) | good (cable tool inefficient) | excellent |
| Consolidated materials less than 500 feet deep | excellent | excellent | not available | excellent | excellent |
| Consolidated materials more than 500 feet deep | good (limited by compressor capacity) | excellent | not available | excellent | excellent |

[1]Includes conventional and wireline core drilling

[2]Air filtration required for monitoring well installation

[3]Not recommended for monitoring well installation in interbedded sand/clay/silt (Cal EPA 1994b)

[4]Includes cable tool & dual-tube methods

### 4.4.1. Sampling device selection

Sampling devices commonly available are split-spoon samplers, thin-wall samplers and core barrels. Samplers may be driven by successive hammer blows (for disturbed samples) or pushed by pneumatic ram (for undisturbed samples). Brass or plastic liners, placed inside the sampler barrel, are often used for ease of retrieval and sample preservation.

For cores collected for visual identification or chemical testing, sample compaction is usually not a critical issue. In this case, split-spoon samplers or core barrels can yield satisfactory results. Samples for chemical analysis should be collected in plastic or brass liners and sealed immediately upon retrieval. The choice of liners and sealing materials should be based on non-interference with the selected analytical method.

Cores intended for physical testing should be collected with as little disturbance as possible. In this case, thin-wall push samplers (for soils) or core barrels (for rock) should be used. The sampler should be able to sample at least a few inches ahead of the drill bit, to minimize disturbance from drilling action or drilling fluid circulation. Cal EPA (1995c) provides more information on soil and rock sampling.

### 4.4.2. Sample coverage

DTSC recommends that every borehole should be continuously sampled (i.e., sampled along its entire depth; also known as **continuous coring**). However, physical and budgetary constraints may not allow this for every site. For example, continuous sampling of every borehole can be economically feasible for small sites, where only a few shallow boreholes are needed; however, for larger sites, where more and deeper boreholes are required, continuous coring may be prohibitively expensive. Additionally, for some geologic materials (e.g., sand and gravel), collecting continuous samples may not be possible, despite the field crew's best efforts.

When continuous sampling of every borehole is not feasible, selected boreholes should be continuously sampled; their number and locations should be chosen to provide representative coverage of site geology and areas of interest to the study.

### 4.4.3. Use of drill cuttings

Drill cuttings are often used as an aid to lithologic identification. This is acceptable only as an adjunct to coring and geophysical logging. Drill cuttings analysis should not be considered a primary diagnostic tool, due to uncertainty of sample origin, mixing from different depths and the washout of fine-grained materials. Mixing is particularly severe with augers; therefore, lithologic analysis of cuttings from hollow stem augers should not be accepted under any circumstances. If mud rotary drilling is used, and cuttings are obtained to supplement cores and geophysical logs, proper mud maintenance should be followed to insure the collection of representative cuttings samples. These mud maintenance procedures are included in Table 12.

## 4.5 Borehole geophysics

### 4.5.1. Description

Borehole geophysical measurements are made by passing measurement probes through a borehole. The record of measurements is called a ***log***. Most borehole geophysical logging methods require an open, fluid-filled hole for proper operation; however, some measurements can be made through casing or in a dry hole. The methods commonly available include:

- **electrical -** uses electrical or electromagnetic energy to measure the electrical properties of soil and rock; useful for lithologic correlation and identification; electrical logs can be used (under ideal circumstances) to estimate water quality and formation porosity;

**Table 12**. Mud and solids control recommendations for lithologic logging.

**Tools Required:**

Mud scale    Marsh funnel kit    Sand content kit

These tools should be kept on-site and maintained in good working order during operations.

**Mud Properties:**

Mud density:sufficient to maintain hole stability, but less than 92 pounds per cubic foot (12.3 lbs/gallon) (71 lbs/ft$^3$ [9.5 lbs/gal] or less satisfactory for most drilling conditions)

Sand content:    less than 4% (2% or less preferable for most drilling conditions)

| | | |
|---|---|---|
| Viscosity[a]: | fine sand | 35-45 seconds |
| medium sand | 45-55 seconds | |
| coarse sand | 55-65 seconds | |
| gravel | 65-75 seconds | |
| coarse gravel | 75-85 seconds | |

**Procedures:**

1.Mud properties should be measured every 20 feet of drilling.

2.If separation equipment is not used (e.g., shakers, desanders), the boring should be circulated clean before mud properties are checked (about 15-20 minutes).

3.Mud property data should be recorded on the lithologic logs.

4.Properties found out of tolerance should be adjusted back into tolerance before drilling resumes.

5.Lag times should be checked at least every 100 feet, by circulating the hole clean, drilling ahead 1 foot and timing the arrival of cuttings at the surface.

6.All mud properties are at the discretion of the driller, should fluid loss, hole stability or equipment concerns arise. However, once these concerns are met, mud properties should be returned to appropriate levels.

[a]Recommended Marsh funnel values from Driscoll, 1986, Groundwater and Wells, p. 351.

- **nuclear** (including gamma logs) **-** measures natural radioactivity or uses radioactive sources to measure absorption or scattering of nuclear energy in surrounding materials; useful for lithologic correlation and identification, some nuclear logs can also be used to estimate moisture content, porosity and density;

- **sonic -** measures velocity of acoustic waves in rock and soil; sonic logs are used primarily to estimate porosity, but can also be used to assess the adequacy of well construction;

- **caliper -** uses flexible feelers to measure borehole diameter, for correcting other logs and assessing hole quality; caliper logs can be used for indirect, qualitative measurements of soil and rock strength.

#### 4.5.2. Tool selection

Each borehole geophysical technique measures a different physical property; therefore, the choice of techniques is dependent upon data needs and site-specific geology. Also, since no single log is conclusive by itself, several borehole techniques are needed to adequately correlate stratigraphic and hydrostratigraphic units. Selecting appropriate borehole logging techniques for use at any site is the responsibility of a qualified geologist or geophysicist. However, specific borehole techniques have been used successfully for years to log a variety of hydrogeologic environments. Therefore, for use in hazardous waste site investigations, the DTSC has presented a recommended list for selecting a basic suite of borehole techniques (Table 13). This table does not list every type of probe that may be used to delineate borehole lithology or aquifer properties. This list represents the *minimal* logging suite adequate for effective geological and hydrogeological interpretation under most circumstances. Additional techniques should be used as site conditions and data needs warrant, based on the targets of interest, hole conditions and data requirements. Tool selection is discussed further in Cal EPA (1995d).

### 4.6 Wells and piezometers

This section briefly discusses the primary attributes of monitor and observation wells, extraction wells and piezometers. The details of their use and construction are more detailed than can be presented here. Please refer to Monitoring Well Design and Construction for Hydrogeologic Characterization (Cal EPA, 1995e) for more information.

#### 4.6.1. Monitoring wells

Monitoring wells are used to assess ground water quality, evaluate aquifer characteristics and determine ground water flow direction and gradient. Monitoring wells may be either single-screen or multi-port designs. **Single screen wells** are screened in only one zone. **Multi-port wells** (though not generally recommended) are screened in several discrete zones, and are designed and constructed to eliminate hydraulic connection between screened zones. Figure 5 illustrates the difference between these two types of well.

Single-screen wells are the predominant type used for hydrogeologic characterization. Acceptable well screen lengths are usually 10 feet or less, although allowances can be made for wells screened across the water table. Only one well should be constructed in a borehole; multiple zones may be monitored by drilling successively deeper boreholes close together

**Table 13**. A) Minimum measurements recommended for a borehole logging suite. Suites may be "wet" or "dry", depending on drilling technique. B) Examples of "wet" and "dry" drilling techniques. Refer to DTSC (1994d) for discussion.

| A. BASIC LOGGING SUITES | | B. DRILLING METHODS | |
|---|---|---|---|
| **Wet Suite** | **Dry Suite** | **Wet Methods** | **Dry Methods** |
| Caliper | Caliper | Mud Rotary | Air Rotary |
| Gamma | Gamma | Reverse Circulation | Percussion |
| Spontaneous Potential | Induction | | Auger |
| Point Resistance | | | |
| Shallow Electrical[1] | | | |
| Deep Electrical[2] | | | |

[1]Includes short normal, shallow focused or shallow induction probes

[2]Includes long normal, deep focused or deep induction probes

[3]Includes shallow and deep induction probes

and installing a single-screened well in each hole. This type of installation is known as a **monitoring well cluster**.

An alternative to clusters, when monitoring multiple fractures or zones in thick aquifers, is the use of multi-port wells. These are acceptable where installing well clusters would be prohibitively expensive (e.g., deep or thick aquifers). The same restrictions on screen length apply to multi-port wells and single-screen wells (this is not a significant issue with current multi-port designs). Multi-port wells should only be installed in individual aquifers. Multi-port wells that monitor more than one aquifer or cross aquitards should not be constructed.

### 4.6.2. Extraction and observation wells

**Extraction wells** are used to withdraw large quantities of water at rates faster than can be obtained from monitoring wells. As a result, extraction wells typically have larger diameters and screen lengths than monitoring wells, and are constructed of more durable materials. Extraction wells are used in pumping tests of aquifers and for removal of contaminated ground water. **Observation wells** are often constructed near extraction wells, for the purpose of monitoring water level changes during aquifer tests or during long-term groundwater extraction and treatment. Observation wells are similar to monitoring wells, and may sometimes be designed as such, but are allowed longer screen lengths to monitor water levels over a larger segment of an aquifer.

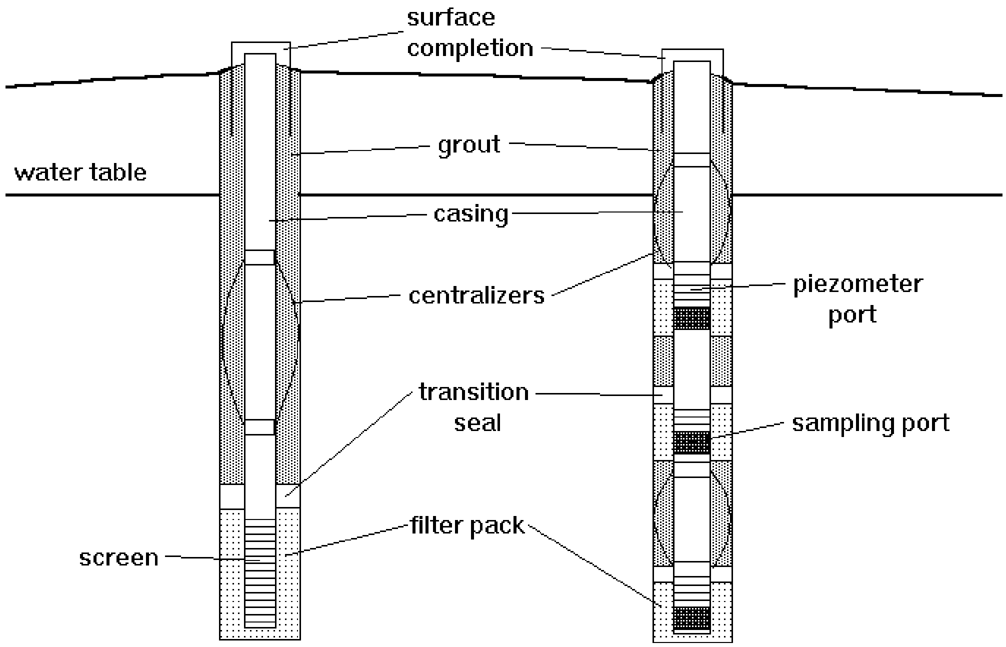


**Figure 5**. Schematic diagram of single-screen and multi-port monitoring wells.

Extraction and observation wells are constructed using methods similar to monitoring wells. The primary concern in extraction well design is screen length. Screens for extraction wells should not be substantially longer than the thickness of the contaminant plume, and should not screen more than a single aquifer. Observation wells may have screen lengths greater than 10 feet in stratified aquifers, to measure an average aquifer response to pumping. However, screen lengths should not be longer than that of the nearest extraction well; screen lengths longer than 30 feet for observation wells are discouraged.

### 4.6.3. Piezometers

Piezometers are used to measure water levels from discrete zones within an aquifer. They are usually cost-effective where water-level information is needed and chemical samples are not required.

Two types of piezometers are in common use (Figure 6). **Open-tube piezometers** consist of a short screen, open bottom or porous tip with casing or tubing extending to the ground surface. Open-tube piezometers are constructed in a manner similar to monitoring wells, but have smaller diameter casing (usually between 0.75 and 2 inches) and shorter screens

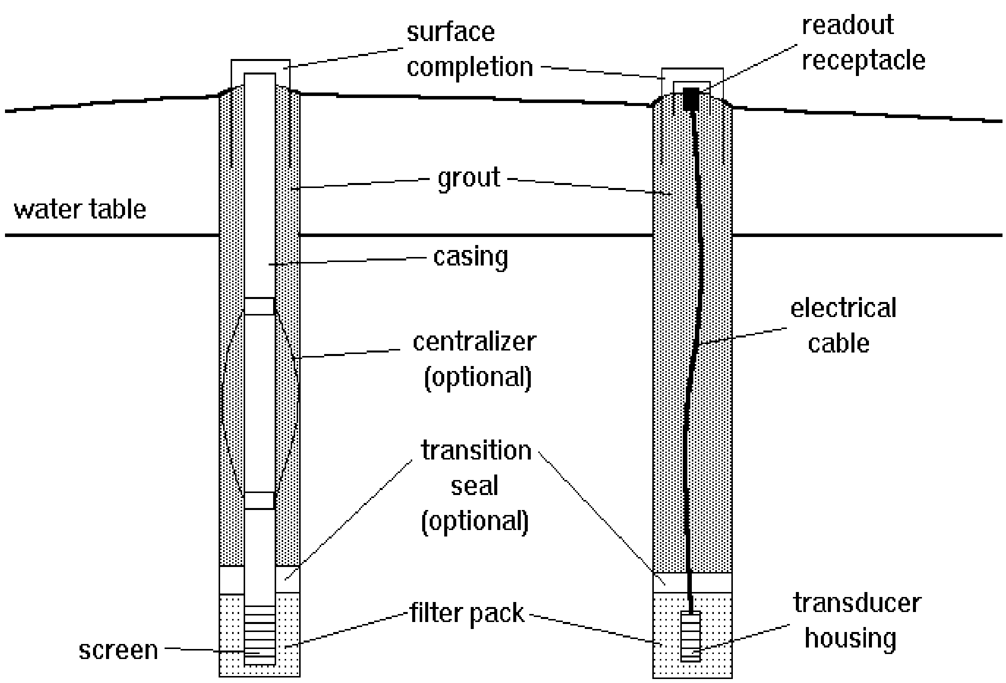


**Figure 6**. Schematic diagram of open-tube and electronic piezometers.

(no more than 5 feet in length). **Electronic piezometers** are pressure transducers mounted inside a filter housing. The transducers are either directly buried or placed inside a short section of screened casing. An electrical cable extending to the surface allows readout of pressure measurements, which are converted to units of height of an equivalent water column above the transducer. Electronic piezometers are useful where frequent measurements are required, such as tidal zones or near streams. These piezometers can be connected to electronic recorders for automated measurement and data acquisition.

### 4.7 Ground water sampling

Ground water sampling involves removing a sample of ground water from a monitoring well, using one of two methods. **Bailers** are narrow containers with one or more check valves, designed to be lowered into a well and filled. The filled bailer is then brought to the surface and the water decanted into appropriate sample containers. **Sampling pumps** are designed to bring ground water to the surface at low rates of flow. The pump (or pump intake) is lowered into the well and used to fill sample containers at the surface. In-situ ground water sampling differs from ground water sampling discussed in this section in that it is a one-time event. In-situ samples cannot be collected over time from the same point.

Sampling pumps are the preferred method of sample collection. Bailers may be acceptable on an individual basis for collecting samples of immiscible contaminants.

Pumps used for ground water sampling should be capable of yielding samples at low flow rates, to minimize sample disturbance. Dedicated pumps (installed in individual wells) are preferred over the use of a single, mobile pump, to reduce the risk of cross-contamination during collection of samples.

Sample preservation and storage guidelines should be strictly followed to ensure reliability and defensibility of sample results. A summary of these guidelines is presented in Table 14. Representative Sampling of Ground Water for Hazardous Substances (Cal EPA, 1995f) provides further discussion of sample collection, preservation and storage.

## 4.8 Aquifer testing

Aquifer tests provide a means of estimating the hydraulic properties of water-bearing zones, by measuring water level changes over time caused by removing or adding water to the aquifer. Two types of aquifer tests are commonly used: **pumping tests**, in which water is extracted at a known rate for a set period of time, and **slug tests**, where a known quantity of water or a solid "slug" of known volume is instantaneously added or removed. In both tests, wells and piezometers are used to remove (or add) water and monitor water level changes.

Slug tests are relatively quick, inexpensive, and can be performed on virtually any well. However, the results yield only a rough estimate of hydraulic conductivity for the formation adjacent to the well. Slug tests can be effectively used to obtain initial hydraulic estimates from representative wells at a site. However, these estimates should always be compared to a smaller number of pumping tests for verification.

Pumping tests, by the physical removal of ground water, measure a larger portion of an aquifer compared to slug tests. The results, therefore, are considered more representative of aquifer characteristics. However, pumping tests are more expensive to run, and often extract large volumes of contaminated water that should be properly disposed. Despite these drawbacks, the reliability of the data makes pumping tests the preferred method for determining aquifer hydraulic properties. Refer to Aquifer Testing for Hydrogeologic Characterization (Cal EPA, 1995g) for further discussion of this topic.

## 4.9 Ground water modeling

Ground water modeling is used to predict the movement of contaminants in ground water and assess the effects of potential cleanup scenarios. The purposes for which ground water models are commonly used can be classified into three categories:

- **Capture zone analysis** is used to assess aquifer response to different extraction scenarios;

- **Plume tracking** is used to model contaminant transport under natural and extraction-influenced ground water flow conditions;

- **Aquifer simulation** represents the highest level of effort for ground water modeling; it is useful for assessing ground water flow and contaminant transport in complex hydrogeologic environments and under transient conditions.

**Table 14**. Sampling and preservation requirements for water samples.

| Parameter | Container[a] | Preservation | Holding Time | No. of Samples x Min. Volume (ml) |
|---|---|---|---|---|
| Acidity | P,G | Cool, 4$^o$C | 14 days | 1 x 100 |
| Alkalinity | P,G | Cool, 4$^o$C | 14 days | 1 x 100 |
| Ammonia | P,G | Cool 4$^o$C<br>$H_2SO_4$ to pH < 2 | 28 days | 1 x 1000 |
| Asbestos | P | Cool, 4$^o$C | 48 hours | 1 x 1000 |
| pH | P,G | determine on-site | 2 hours | 1 x 50 |
| Radioactivity | P,G | $HNO_3$ to pH < 2 | 6 months | 1 x 1 gallon |
| Total Organic Halides (TOX) | Amber G-V | Cool, 4$^o$C<br>1 ml 0.1M $Na_2SO_3$, $HNO_3$ to pH < 2 | 7 days | 3 x 100 |
| Total Organic Carbon (TOC) | P,G | Cool 4$^o$C | 28 days | 1 x 100 |
| Chloride | P,G | none | 28 days | 1 x 100 |
| Cyanide | P,G | NaOH to pH > 12; 0.6 g Ascorbic acid if $Cl^-$ present | 14 days | 1 x 1000 |
| Fluoride | P,G | none | 28 days | 1 x 500 |
| Nitrate | P,G | Cool, 4$^o$C | 48 hours | 1 x 500 |
| Sulfate | P,G | Cool, 4$^o$C | 28 days | 1 x 200 |
| Sulfide | P,G | Cool, 4$^o$C<br>2 ml Zinc acetate<br>NaOH to Ph > 9 | 7 days | 1 x 1000 |
| Chromium VI | P,G | Cool, 4$^o$C | 24 hours | 1 x 500 |
| Dissolved Metals (except Cr VI) | P,G | Filter on-site<br>$HNO_3$ to pH < 2 | 6 months (except Hg, 28 days) | 1 x 1000 |

[a]P = Polyethylene container with polypropylene closure.
G = Glass container with Teflon-lined closure.
G-V = Glass VOA (volatile organic analyte) vial or bottle with Teflon septum.

**Table 14 (continued)**. Sampling and preservation requirements for water samples.

| Parameter | Container[a] | Preservation | Holding Time | No. of Samples x Min. Volume (ml) |
|---|---|---|---|---|
| Total Metals | P,G | $HNO_3$ to pH < 2 | 6 months (except Hg, 28 days) | 1 x 1000 |
| Extractable (semi-volatile) Organics | G | Cool, 4$^oC$ | 7 days to extraction, analysis 40 days after extract | 1 x 1000 |
| Purgeable (volatile) Organics | G-V | Cool, 4$^oC$ | 14 days | 2 x 40 |
| Purgeable Aromatics | G-V | Cool, 4$^oC$ HCl to pH < 2 | 14 days | 2 x 40 |
| Acrolein & Acrylonitrile | G-V | Cool, 4$^oC$ | 14 days | 2 x 40 |
| Gasoline | G-V | Cool, 4$^oC$ | 14 days | 2 x 40 |
| Pesticides & PCB's | G | Cool, 4$^oC$ | 7 days to extraction, analysis 40 days after extract | 1 x 1000 |
| Phenols | G | Cool, 4$^oC$ $H_2SO_4$ to pH < 2 | 7 days to extraction analysis 40 days after extract | 1 x 1000 |
| Oil & Grease | G | Cool, 4$^oC$ $H_2SO_4$ to pH < 2 | 28 days | 1 x 1000 |

[a]P = Polyethylene container with polypropylene closure.
G = Glass container with Teflon-lined closure.
G-V = Glass VOA (volatile organic analyte) vial or bottle with Teflon septum.

Three types of ground water models are recognized (Javandel et al., 1984): analytical, semi-analytical and numerical.

**Analytical models** provide a direct solution of the equations governing contaminant transport. One-dimensional and two-dimensional models are commonly available. However, the direct solutions can only be derived by assuming simple boundary conditions and a homogeneous, isotropic aquifer with steady-state, uniform flow. Analytical solutions are not tractable for multiple sources and sinks. Therefore, though useful as a planning tool, analytical models are not generally reliable for remedy screening or remedial design.

**Semi-analytical models** combine analytical solutions with numerical approximations to model contaminant transport. Semi-analytical models also assume homogeneous, isotropic conditions. Steady-state, uniform flow and simple boundary conditions are also prerequisites, but can be adapted to transient conditions for some applications. Unlike analytical models, semi-analytical techniques can handle multiple sources and sinks of varying dimensions. Semi-analytical methods are only applicable to two-dimensional (2-d) analysis and cannot be applied to three-dimensional problems. However, where ground water flow conditions can be reasonably approximated by two-dimensional steady state flow, semi-analytical models can provide useful information for remedy screening and remedial design.

**Numerical models** utilize iterative approximations to the equations governing fluid transport. This approximation allows detailed analysis of fluid transport in aquifers. Numerical analysis can handle spatial variations in aquifer parameters (such as hydraulic conductivity and porosity), as well as temporal changes in ground water flow. Complex boundary conditions and three-dimensional (3-d) transport can also be managed by numerical analysis. The main drawbacks to numerical modeling are that the models require significant experience to run, data management and model calibration are often time-consuming, and sufficient data do not always exist to justify such detailed modeling efforts. Often, lack of detailed aquifer data yields numerical results that are no better than could be obtained using simpler (and cheaper) semi-analytical models. However, in complex hydrogeologic environments and where adequate data exist, numerical modeling can yield superior results. Ground Water Modeling for Hydrogeologic Characterization (Cal EPA, 1995h) provides more discussion on the use of numerical models.

The selection of an appropriate ground water model often hinges on whether a two-dimensional or three-dimensional analysis is needed. Two-dimensional models are sufficient for most applications. However, where vertical gradients are a significant factor in contaminant transport, a 3-d simulation should be used. The decision whether to select a 2-d or 3-d model is site-specific. Therefore, the existence and significance of vertical gradients should be assessed at every site before selecting a ground water model.

Ultimately, the success of any ground water model is dependent on data quantity and quality, and the knowledge and skill of the modeler. Every model is a simplified representation of complex phenomena, and as such have inherent limitations. A modeling technique or algorithm may neither be appropriate for a given application, nor may sufficient data exist for its proper use. Often, different models may be required to fulfill different needs. The modeler should ensure that any selected model is appropriate to the situation and question to which it is applied, and that sufficient data exist to yield a correct answer.

# 5. PRESENTATION OF SITE CHARACTERIZATION DATA

## 5.1 Technical Memoranda

Technical memoranda are essentially informal RI progress reports. Their purpose is to provide timely information on current RI activities and present preliminary information for review by the regulatory agencies. Regular reporting through technical memoranda can help identify problems and data gaps early, thereby enabling a consensus to be developed between responsible parties and regulatory agencies prior to delivery of the formal RI reports.

Technical memoranda should be developed on a semiannual schedule, and should summarize information gathered during the preceding period. Data to be included in technical memoranda include the following (where applicable):

- boring and well location maps,
- lithologic, geophysical and cone penetrometer logs,
- monitoring well construction logs,
- geologic maps,
- geologic cross sections,
- aquifer test data,
- ground water models, and
- summaries of ground water quality data.

Data presented in technical memoranda need not be cumulative. However, interpretations presented in earlier memoranda (e.g., the conceptual model) should be updated as warranted by new information. Reporting Hydrogeologic Characterization Data from Hazardous Substance Release Sites (Cal EPA, 1995i) provides more information on technical memoranda reporting.

## 5.2 Ground Water Quality Reports

Ground Water Quality Reports are summaries of ground water monitoring data only. Since ground water sampling usually occurs according to a more frequent schedule than other RI activities, submittal of ground water quality reports should follow a quarterly schedule and should contain the following:

- cumulative monitoring data,
- well location flags (i.e., up-gradient, down-gradient, cross-gradient, within plume),
- well screen elevations,

- brief discussion of results and trends,
- plume maps (usually needed only if significant changes have occurred from the previous quarter).

With each technical memorandum, a ground water quality summary report should be prepared. As its name implies, this report summarizes ground water sampling efforts for the preceding reporting period. Contents of the summaries are similar to the quarterly reports, with the following additions:

- seasonal plume maps for the preceding year,
- seasonal ground water elevation maps for the preceding year,
- cumulative hydrographs for all monitoring wells, and
- a review of data needs for ground water sampling and proposed amendments (additions or deletions).

Unlike the technical memoranda, ground water quality reports are cumulative (i.e., all previous sampling results are included in each report). This enables easier identification of trends in contaminant migration or possible errors in the data. Cal EPA (1994i) provides additional discussion of ground water quality reporting contents.

### 5.3 RI Reports

Remedial Investigation (RI) reports provide the formal documentation of field investigation activities. The purpose of the RI is to provide the final results of the field investigations and the results of the baseline risk assessment. For hydrogeologic characterization, RI reports include the following:

- Contaminant composition,
- Source areas,
- Extent of soil and ground water contamination,
- Contaminant migration, and
- Points of exposure.

The suggested content for RI reports is presented in Table 15. Additional discussion of RI reports is provided in USEPA (1988) and DTSC (1993).

Conciseness should be a goal for all RI reports. With regular reporting through technical memoranda, an RI report may simply summarize previously reported information. Text should be minimized wherever possible by the use of tables, graphs and illustrations. Additional information on the use of illustrations for data reporting is provided in Cal EPA (1995i).

**Table 15**. Recommended RI Report Content. Data presented in the RI report should be sufficient for development and screening of remedial alternatives. Adapted from USEPA (1988) and DTSC (1993).

1. Study Area Investigation

Discuss field activities associated with site characterization. These activities may include assessment or monitoring of some, but not necessarily all, of the following:

| | |
|---|---|
| Surface features | Contaminant source |
| Meteorology | Surface water and sediment |
| Soil and Vadose zone | Geology |
| Ground water | Human population |
| Ecology. | Historical land use |

2. Physical Characteristics of Study Area

Provide results of field activities; the following areas may be covered:

| | |
|---|---|
| Surface features | Meteorology |
| Geology | Surface water hydrology |
| Soils | Hydrogeology |
| Ecology | Demography and land use. |

3. Nature and Extent of Contamination

Present data on contaminant composition and extent for some, but not necessarily all, of the following media:

| | |
|---|---|
| Source areas | Soils and vadose zone |
| Ground water | Surface water and sediments |
| Air. | |

Describe any spatial or temporal variations or trends in contamination.

4. Contaminant Fate and Transport

Describe potential routes of migration and estimated persistence of contaminants in the study area. Include physical, chemical and biological factors of importance for media of interest. Discuss factors affecting contaminant for media of importance. Present modeling methods and results if applicable.

5. Summary and Conclusions

Summarize results presented in previous sections, describe data limitations and any recommendations for additional work. Present recommended remedial action objectives.

Appendices

Appendices may include, but are not limited to, technical memoranda, analytical data, QA/QC evaluations and risk assessment methodology as appropriate.

## 6. RI DATA REQUIREMENTS FOR FEASIBILITY STUDIES

As presented in USEPA (1988), every feasibility study requires that cleanup alternatives be developed and screened concurrent with the remedial investigation. Screening involves the evaluation of alternatives based on effectiveness, implementability and cost. Remedy selection, design and implementation are based on these evaluations. Therefore, information collected during the RI should be sufficient to support these evaluations.

For remedies involving the extraction and treatment of ground water, the following data needs are critical to the remedy screening:

- contaminant composition and concentration,
- extraction and injection well locations,
- extraction and injection rates
- aquifer thickness, transmissivity and porosity, and
- calculation or modeling of capture zones for contaminant extraction.

A practice occurring with increasing frequency is the attempt to defer selected data needs to the remedial design. Occasionally, these deferrals are critical to the evaluation of the selected remedy. Although a comprehensive remedial design is neither necessary nor practical for the RI/FS, collection of data needed for adequate remedy screening should not be deferred to the remedial design. Therefore, all data critical to remedy screening should be collected during the RI/FS. Deferral of critical data needs to the remedial design should not be considered an acceptable practice.

## 7. CONCLUSION

This guidance document was developed to provide a framework, that can be applied statewide, for conducting hydrogeologic characterizations of hazardous substance release sites under the authority of the DTSC. This document provides a process model for hydrogeologic investigations, summarizes commonly used methods and general guidelines for their application, and presents general objectives for completing the hydrogeologic portion of any RI/FS. Additionally, minimum content and reporting requirements are outlined to substantiate achievement of these objectives.

The investigation methodology presented in this document is closely related to the RI/FS process presented by the USEPA. This process, in general, is similar for every RI/FS. In detail, however, technical, logistical and budgetary constraints, that exist at every site, may result in acceptable minor deviations from this process. No guidance document can account for these site-specific variations. Therefore, guidance is no substitute for experience and professional judgement. Exceptions to these guidelines should be anticipated, and independent judgement, based on experience, should be exercised where needed. Despite these limitations, the guidelines presented in this document provide an acceptable starting point for all hydrogeologic investigations, and can assist in acceptable data collection, appropriate analysis and adequate presentation of findings, in a consistent fashion, for all hazardous substance release sites in California.

## 8. REFERENCES


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